

PASSIVE MICROWAVE REMOTE SENSING OF ATMOSPHERIC WATER VAPOR, CLOUD LIQUID, AND TEMPERATURE

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ABSTRACT

Passive microwave techniques for sensing the earth's atmosphere provide powerful tools for understanding and monitoring its dynamics. These techniques exploit the microwave and millimeter-wave emissions of atmospheric constituents. Tuning a sensitive radio receiver, termed a radiometer, to these emissions allows the atmosphere to be probed remotely from satellites, airplanes, and the earth's surface. Microwave radiometers can sense water vapor, atmospheric temperature profile, cloud liquid, and trace concentrations of many atmospheric gases.

Microwave radiometers have applications in many areas: weather prediction, pollution forecasting, aviation, climatology, spacecraft tracking, geodesy, and atmospheric chemistry. Four specific applications for low-cost commercial radiometer systems are explored in this paper. Microwave temperature profilers (MTPs) can provide real-time detection of temperature inversions that trap automobile emissions and industrial pollution near the ground. Timely, accurate prediction of weather conditions conducive to creating high pollution levels has significant value in mitigating pollution hazards. Water vapor radiometers (WVRs) can measure the total atmospheric water burden (*e.g.*, water vapor and cloud liquid) which could enhance weather predictions and rain forecasts. Both MTPs and WVRs could support federal efforts to validate and improve the performance of global climate models. Critical climatic measurement needs include measurement of horizontal distribution of both cloud liquid and water vapor. Finally, airport-based radiometers could be used to predict aircraft icing conditions by detecting clouds bearing supercooled liquid. Ground-based radiometer determinations of the temperature profile and amount of cloud liquid coupled with ceilometer or radar determinations of cloud height allow identification of sub-freezing cloud liquid.

Widespread application of radiometric remote sensing systems has been restricted by costs. Plumbed-waveguide radiometer systems for monitoring water vapor, cloud liquid, or temperature profiles cost between \$120K and \$500K depending on the specific application. It is believed that significant price reductions can be achieved through mass production, application-specific designs, and use of monolithic or hybrid microwave integrated circuit (MMIC and MIC) technology. Recent advances in MIC technologies promise to reduce production costs by allowing radiometers to be etched on an integrated circuit. Conversion to MIC will also reduce the size and power requirements thereby lowering costs of the associated power, antenna pointing, and temperature regulation subsystems. It is also anticipated that the compact size and reduced power consumption will translate into improved temperature control which will increase radiometer stability. Preliminary studies indicate that system cost reductions ranging from a factor of three to eight appear feasible with minimal development costs. We believe these cost reductions will stimulate widespread commercialization of radiometric atmospheric remote sensing.

1 INTRODUCTION

Atmospheric radiometers have been primarily developed as research tools. Radiometers currently fly on satellites measuring atmospheric temperature, polar ozone, water vapor, stratospheric chlorine, and cloud liquid. Ground-based radiometers are being employed for climate research, weather, satellite communications, astrophysics, and aviation safety. Due to these activities, radiometric techniques are well developed and the instrumentation is mature. Many current uses have commercial value. However, the widespread application of radiometric technology has been restricted by cost. This could change; with development of a commercial market for microwave devices and integration of microwave circuit technology, there is potential for significant cost reduction.

This paper intends to provide an overview of atmospheric radiometry and potential commercial markets. First, is a top-level analysis of how atmospheric radiometry is used to measure the atmosphere. This is followed by a general description of radiometer design and strategies for achieving future cost reduction. Finally, (discussion will center on four applications with commercial value.

RADIOMETRIC REMOTE SENSING OF THE ATMOSPHERE

The atmosphere emits (and absorbs) a continuous spectrum of microwave and millimeter-wave radiation [1]. As illustrated by Figure 1, tropospheric absorption spectra are dominated by broad, discrete, water vapor and oxygen spectral lines superimposed upon a continuum. Although the 22 GHz water vapor line and 60 GHz oxygen band are the result of different processes, they are both primarily broadened by molecular collisions [1]. Continuum emissions are produced by water vapor, liquid water (clouds), and to a lesser extent, nitric oxide [1].

The 22.2 GHz emissions of atmospheric water vapor are routinely used for remote sensing. Weakness of this spectral line and minor contributions from other radiative sources makes it a popular choice for many remote sensing applications. Measurement of water vapor emissions can be used to determine the columnar abundance of water vapor. Continuum emissions from cloud liquid are broadband and are therefore usually sensed in either the 30 to 38 GHz or 85 to 100 GHz spectral windows. Measurement in these spectral windows minimizes contamination from other sources of emissions. Radiometric measurements of cloud liquid allows the columnar liquid content of a cloud to be determined. In fact, radiometry is the only technique that

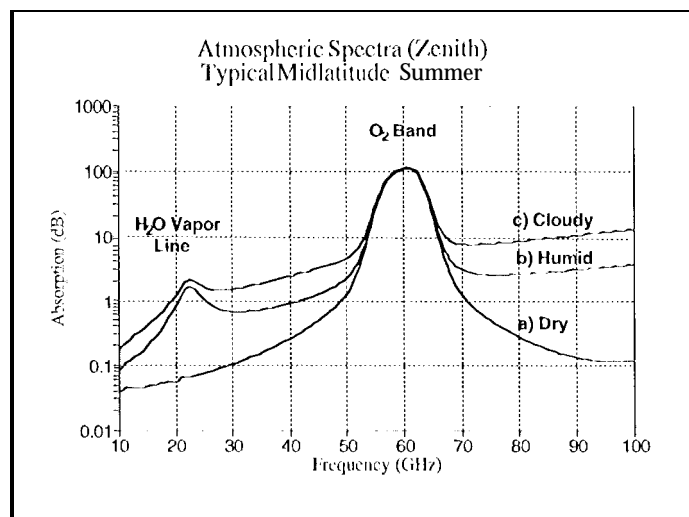


Figure 1. Typical midlatitude summer atmospheric spectra for a) no water vapor, b) a humid day, and c) a humid and cloudy day.

can determine a cloud's total liquid content. (Radar echoes are better correlated with drop size and shape than total liquid content.) Additionally, radiometry is the only technique able to accurately sense vapor along an arbitrary line-of-sight during cloudy weather. However radiometry cannot be used to retrieve either cloud altitude or high-resolution vapor profiles. In contrast to the weak emissions of water, the 60 GHz oxygen band is strong or optically thick. As will be discussed, this makes this spectral band useful for measuring atmospheric temperature profiles.

The intensity of microwave or millimeter-wave energy emitted by an atmospheric gas can be quantified in terms of a brightness temperature [2]. A physical interpretation of the brightness temperature is that it is the temperature of a blackbody that emits the same intensity of radiation per unit bandwidth as the atmospheric gas being observed. This can be quantified using the Rayleigh-Jeans approximation

$$T_b(\nu) = \frac{\lambda^2}{2k} I(\nu) \quad (1)$$

where $T_b(\nu)$ is the brightness temperature, k is Boltzmann's constant (1.381×10^{-23} J/K), λ is the radiation wavelength, and $I(\nu)$ is the radiation intensity [2]. The intensity of radiation received by a radiometer is the radiation being emitted minus the radiation being absorbed integrated along the atmospheric path being viewed. To calculate the radiation received from an emission region located a distance s_0 from the observation point, the total radiative transfer needs to be calculated using

$$T_b(\nu) = T_{b0} e^{-\tau(s_0)} + \int_0^{s_0} T(s) e^{-\tau(s)} \alpha ds, \quad (2)$$

where the T_{b0} is the brightness temperature of the source or background, $T(s)$ is the temperature of intervening media at distance s , and $\tau(s)$ is the optical depth at distance s [2]. The first term represents the source and the second term represents the intervening media, insight can be gained by examining this integral expression at the two limits of opacity. First we simplify the expression by assuming that the atmosphere is at a constant temperature, $T(s) = T$. This allows temperature, T , to be a multiplicative factor for the integral expression. For an optically thin atmosphere [2],

$$\int_0^{s_0} T(s) e^{-\tau(s)} ds \approx T \tau_{s_0} \quad \text{for } \tau_{s_0} \ll 1 \text{ and } T(s) = T. \quad (3)$$

in this case the brightness temperature is just the physical temperature times the opacity or optical depth. Since the optical depth is proportional to the concentration of the absorbing/emitting gas, then the brightness temperature is proportional to the line-of-sight gas content weighted by its physical temperature. In contrast, an optically thick atmosphere yields [2]

$$\int_0^{s_0} T(s) e^{-\tau(s)} ds \approx T \quad \text{for } \tau_{s_0} \gg 1 \text{ and } T(s) = T. \quad (4)$$

Thus, the brightness temperature of an optically thick gas is simply the media's physical temperature.

Given a sufficiently accurate description of the meteorological conditions, the atmospheric opacity or emission spectrum can be calculated. In contrast, the solution to the inverse problem is not unique. Emission measurements at a limited number of frequencies will not allow the various

atmospheric parameters to be uniquely determined. Interpretation of the radiometric measurements usually requires that some atmospheric parameters be estimated. For example, cloud and vapor sensing using a dual-frequency water vapor radiometer requires that the atmospheric temperature be estimated. The effect of an estimated parameter on the retrieval accuracy can be reduced with the judicious choice of radiometric frequencies. A detailed description of various techniques used to retrieve atmospheric water vapor and cloud liquid from measurements of brightness temperatures is beyond the scope of this article; however it is well documented in the technical literature [3, 4].

Optically thin regions of the atmospheric spectrum are used to sense atmospheric water. Thus radiometric measurements furnish a signal proportional to the atmospheric opacity times the physical temperature. The first step in retrieving water vapor and cloud liquid from emission measurements is to estimate a mean atmospheric temperature [3]. This is the average value of the physical temperature of the atmospheric water which ranges from 260 K to 280 K. It can usually be estimated to within 2% using surface temperature measurements. The mean temperature allows the opacity or atmospheric brightness temperature to be calculated. The atmospheric brightness is a sum of emissions from water vapor, liquid water (clouds), oxygen, and astronomical sources. To retrieve either water vapor or cloud liquid, corrections need to be applied for these other emission sources. Corrections for oxygen emissions can be computed from ground-based pressure measurements [3]. Beam-averaging causes most astronomical emission sources to be insignificant when measurements are made with a moderate beamwidth antenna ($\theta > 2^\circ$). The S1111 is an exception that usually frustrates attempts to make measurements in its direction. The other source needing correction is the microwave cosmic background which will appear as a constant 2.74 K offset in the radiative transfer equation [3]. Once these corrections are made, cloud liquid can potentially be determined from measurement at a single frequency. In contrast, water vapor determinations usually require **two** frequencies: one at the 22 GHz water vapor spectral line and the other at a cloud sensing frequency (to provide a correction for liquid emissions). Measurements at additional frequencies are used to improve the retrieval accuracy for both water vapor and cloud liquid [3, 4].

Temperature profiling exploits the optically thick emissions of the 60 GHz oxygen band. In this case, the brightness temperature equals the physical temperature of the gas [3, 5]. For the atmosphere which has a varying temperature structure, radiative transfer through the medium needs to be treated. This is realized with a weighting function, $W(s)$, that describes the distribution of received thermal emission as a function of distance between the emission source and the radiometer. For ground-based temperature profiling, frequencies are chosen with optical depths corresponding to a distance of a hundred meter to several kilometers. Assuming, for simplicity that atmospheric opacity is constant with altitude, the weighting function is exponential $W(s) = e^{-s}$ [5]. Using the weighting function formulation, the measured brightness temperature reduces to

$$T_b = \frac{\int_0^\infty W(s)T(s)ds}{\int_0^\infty W(s)ds} \quad (5)$$

where $T(s)$ is the temperature structure of the atmosphere with respect to altitude, s [5]. For a medium with a linear variation in temperature, *i.e.* $T(s) \sim s$, the measured brightness temperature equals the atmospheric physical temperature at a distance of one optical depth, $s_{0.1}$, that is where the

weighting function equals $1/e$. Therefore a temperature profile can be derived by measuring atmospheric emissions at a series of frequencies each corresponding to different optical depths. Once the average temperature is known for each optical depth then the data can be inverted to generate a temperature profile.

For ground-based and airborne applications the altitude resolution can be enhanced using a technique developed by Bruce Gary at JPL [5]. It exploits the fact that horizontal atmospheric temperature gradients are more than an order of magnitude smaller than vertical gradients. Making radiometric measurements at non-zenith elevation angles allows the effective altitude corresponding to a given optical depth to be varied [5]. The effective altitude for temperature retrieval at an elevation angle, θ is just the optical depth at that elevation angle projected onto the vertical axis. Thus for optical depth s_a and an elevation angle of θ , the effective altitude h_a for the temperature retrieval is simply $h_a = s_a \sin \theta$. For a horizontally stratified atmosphere, the brightness temperature at elevation angle θ can be associated with an effective altitude, h_a using [5]

$$T_b(\theta) = T(h_a) = T(s_a \sin(\theta)) \quad (6)$$

The atmospheric temperature profile can then be constructed using multi-frequency brightness temperature measurements at a series of elevation angles.

RADIOMETERS

Radiometers are sensitive radio receivers that generate an output voltage that is proportional to the power incident at the antenna. A generic block diagram for a total-power radiometer is illustrated in Figure 2. The actual implementation can employ either a heterodyne or diode detect receiver. Although the basic design parameters are determined by specific applications, there are some basic principles underlying radiometer design.

The power emitted by an atmospheric gas is simply

$$P_i = kTB \quad (7)$$

where k is Boltzmann's constant, T is the brightness temperature of the gas in Kelvin, and B is the measurement bandwidth in hertz. The total power measured by the radiometer is the system noise which is the sum of the atmospheric and radiometer noise. The atmospheric noise ranges from 7 K to 300 K depending on the atmospheric opacity and radiometer noise ranges from 100 to 600 K depending primarily on the noise figure of the front end amplifier. Consequently, the total power incident at the radiometer measured with a 200 MHz bandwidth will range from 0.3×10^{-12} and 2×10^{-12} watts (or -95 dBm to -87 dBm). To measure the brightness temperature of a gas with 0.5 K resolution and the same bandwidth requires detecting power differences of 1.4×10^{-15} watts.

The input power levels also determine the system gain. The RF gain and IF gain (if applicable) are chosen to match the linear region of the detector with a typical value being 50 dB. DC gain is selected to generate a voltage that is optimized for the chosen analog to digital conversion technique. The system gain can then be expressed as a proportionality relationship between the incident atmospheric temperature, T_a , and the radiometer output voltage, V ,

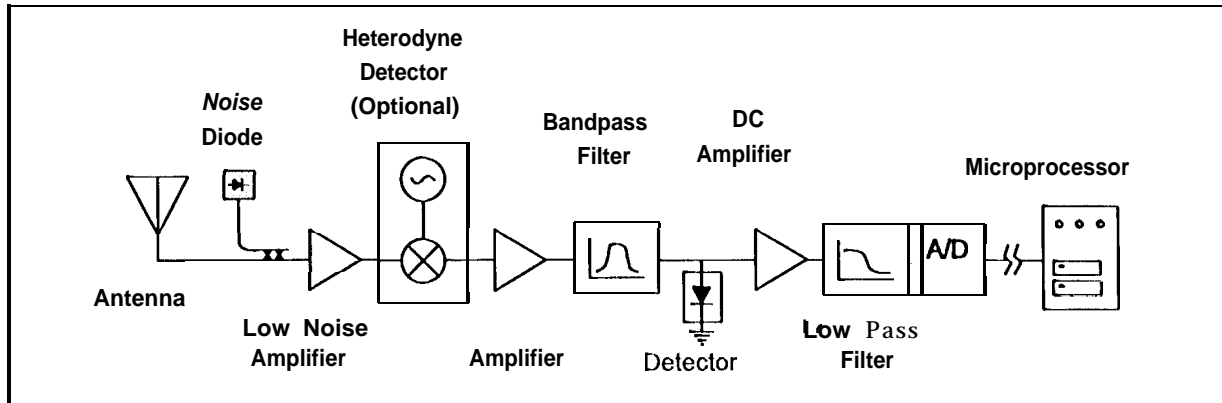


Figure 2. Generic Block Diagram for a radiometer receiver.

$$T_a = c (V - V_o) \quad , \quad (8)$$

where V_o is proportional to the receiver noise power and c is the system gain [4]. Reasonable values of system gain span from 1 V per 10 K to 1 V per 300 K. The requisite gain stability is simply the measurement accuracy divided by the total system temperature. For example, a 0.5 K noise temperature accuracy measured with 450 K of radiometer system noise (50 K atmosphere plus 400 K radiometer noise) requires 0.5/450 or 0.1 % gain stability. In other words a 0.1 % gain fluctuation will masquerade as a 0.5 K change in the incident atmospheric power.

The radiometer measurement precision is limited by fluctuations in measured thermal noise. The magnitude of these fluctuations is a function of the total system noise and can be reduced by integrating over time. To make a measurement with a T_R precision requires an integration time, τ ,

$$\tau = \frac{T_s^2}{A T_R^2 B} \quad (9)$$

where T_s is the radiometer system noise [2]. For measurement of a 260 K atmospheric temperature with 0.2 K precision using 300 K receiver with a 200 MHz bandwidth will require a 40 ms integration time. A wider bandwidth and lower receiver noise will reduce the integration time.

The instrumental frequency stability requirements are determined by the structure of the atmospheric spectrum and requisite measurement accuracy. If measurements are being made on the wing of a spectral line, then a frequency shift towards the spectral peak will cause an increase in the measured emissions. Requirements for stability are usually in the range of 100 kHz to 100 MHz depending on the application.

The primary technical challenge in radiometry is to develop a high gain (> 70 dB) receiver that is stable to a tenth of a percent. Temperature-induced gain and frequency changes tend to limit radiometer stability. Therefore, good thermal design and temperature control is essential for accurate radiometric measurements. Other sources of gain variations include power supply drifts, mechanical vibration, and RFI; however these can be minimized with good design practices.

There are several techniques for calibrating radiometers. Gain, c , can be calibrated with a measurement of two calibration targets each at a different temperature, T_{hot} and T_{cold} . The output voltage associated with each of these measurements, V_{hot} and V_{cold} , can then be used to calculate c [2]

$$c = \frac{T_{hot} - T_{cold}}{V_{hot} - V_{cold}} \quad (10)$$

Similarly, the receiver noise power, V_o , can also be calculated,

$$V_o = \frac{1}{2} \left(V_{hot} + V_{cold} \right) - \frac{1}{c} (T_{hot} + T_{cold}) \quad (11)$$

Targets can be built from microwave absorbers. Measurements at ambient temperatures are usually used for one calibration point. Absorbers placed in liquid nitrogen (77 K) are another popular choice for a second calibration point. Construction of targets for high accuracy applications is a bit of an art and is discussed in detail in reference [6].

The gain can also be calibrated with one or more noise diodes. Injecting noise into the antenna signal path is an inexpensive method for monitoring radiometer gain and receiver noise. By using two diodes coupled with different strengths a real time calibration is possible. Other techniques for calibration include "tipping" the radiometer elevation angle to use the atmosphere as a calibration target and using internal hot and cold loads [4].

Antennas for radiometry do not need high efficiency; however they require low side lobes and spillover. The need for reducing side lobes and spillover is best illustrated with an example. Consider a sidelobe that contributes 1% to the total received energy: when directed toward the ground ($T_{bg} = 300$ K) it will introduce an error equal to 1% of T_{bg} or 3 K. Sidelobes and spillover are usually specified not to exceed 30 to 40 dB. To minimize sidelobes and eliminate spillover, radiometers tend to be designed with corrugated horn antennas.

In addition to the radiometer RF electronics there are a variety of application-specific design issues such as antenna beamwidth and pointing needs, power requirements, communications, instrument control, and data acquisition. An example of a general purpose water vapor radiometer is the JPL J-series radiometer which is shown in figure 3 [7]. It was developed to be compact, portable with self-diagnostic capability. It senses water vapor and cloud liquid at 20.7, 22.2, and 31.4 GHz. The antenna and RF electronics are housed in the top box and power supplies and instrument controller are housed in the bottom. The antenna is mounted horizontally and is pointed at a 45° mirror. This mirror can be rotated to vary the antenna elevation angle and the whole top unit swivels to vary azimuth pointing. This

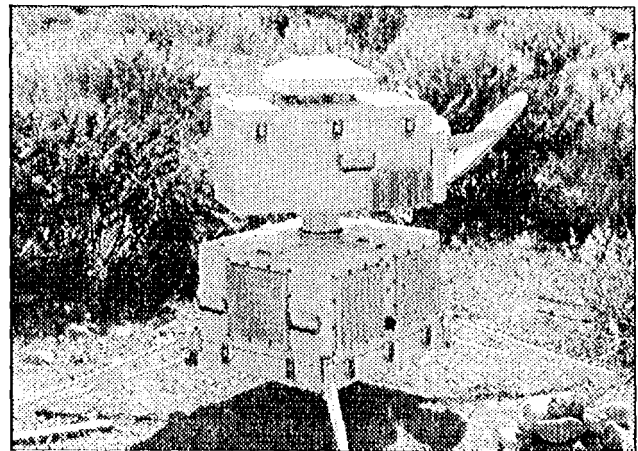


Figure 3. The JPL J-series water vapor radiometer. Ref [7].

radiometer has been a workhorse for JPL, providing ground-based verification of satellite radiometer performance, collecting Ka-band propagation statistics for modeling earth-to-space telecommunication links, determining water vapor-induced atmospheric propagation delays, performing basic research in atmospheric dynamics, and participating in climate measurement campaigns.

A new generation of radiometers is being developed using monolithic and hybrid microwave integrated circuit (MMIC and MIC) technology. An initial proof-of-concept hybrid MIC radiometer channel was developed at JPL in 1992 (see figure 4 [8, 9]). Since that time, several satellite instrument programs have started development of MIC and MMIC radiometers. These radiometers will be used to make astrophysical measurements, measure atmospheric water vapor, and monitor atmospheric temperature. For satellite applications, MIC and MMIC technology has been selected to achieve significant size, weight, and power reductions.

We believe significant cost reductions can be achieved through application-specific design and use of MMIC and MIC technology. Cost drivers for radiometer design include antenna beamwidth, number of measurement frequencies, antenna pointing capability, size, power requirements, and thermal control. By performing a thorough review of a radiometer application, only required features will be included in the design. For example, it may be decided that only zenith pointing is necessary for weather observations. That design decision will eliminate the cost of mirrors and motors needed to steer the radiometer pointing angle.

Additionally, when radiometer production increases from the current rate of several units per year to dozens per year then there will be a benefit to implement the electronics using MIC technology. Being able to etch a radiometer on an integrated circuit will reduce the labor costs associated with assembling the RF section. Additionally, the smaller size and lower power requirements will reduce the capacity of power supplies, enclosure size, temperature control, power consumption, etc. Each of these reductions will further drive down costs.

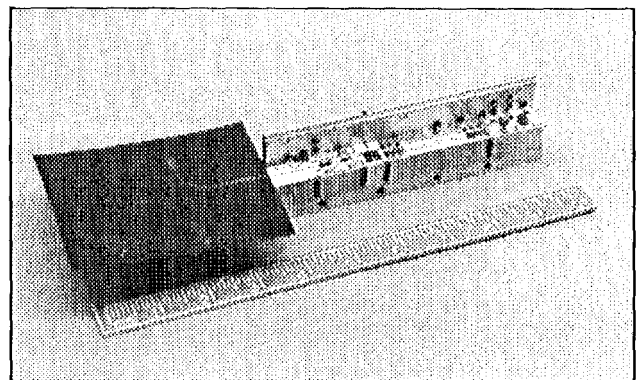


Figure 4. *A proof-of-concept, single-channel, MIC radiometer developed at JPL. Refs. [8, 9].*

POTENTIAL COMMERCIAL APPLICATIONS OF RADIOMETERS

Air Pollution Forecasting

In urban areas, temperature inversions can trap auto emissions and industrial pollution near the ground creating significant health hazards [10]. Timely and accurate prediction of weather conditions conducive to high pollution levels have economic value. For example, forecasts can be used to regulate discharges from large emission sources. Several cities require power companies to switch to cleaner-burning fuels during periods when strong inversions are present. Since cleaner fuels are more expensive than the heavier, high-sulfur fuels, savings could be realized from improving forecast accuracy. Improved air quality can also be achieved in cities that have authority

to impose wood-burning (fireplace) bans. In addition, predictions allow alerts to be issued to groups that are most sensitive to air pollution such as young children, asthmatics, and the elderly.

Currently, local pollution forecasts are developed from general weather service predictions supplemented with local launches of radiosondes (balloons instrumented with meteorological sensors). Forecasts are restricted by the limited spatial and temporal resolution of these available data sources. A microwave temperature profiler would enhance existing observation systems since they can determine the atmospheric temperature profile as frequently as several times per minute. They can operate autonomously and can be accessed via telephone or radio link as required. This technology could significantly improve the temporal and spatial resolution of current balloon-based monitoring systems. The current cost of expendables such as radiosondes would make a low cost temperature profiler attractive. At current spending levels, savings realized over several years could be used to setup a profiler network allowing ground-level weather changes to be tracked.

It is worth mentioning that for this application there are several advantages of radiometric temperature profilers over a competitive temperature profiler technology, radio-acoustic sounding [11]. Profiling radiometers can be compact, reliable, low power, and inexpensive to operate. Additionally, since radiometers do not transmit acoustic or radio energy, they are "good neighbors" and can be deployed in urban environments. Although climetric profilers do not provide the altitude resolution of a RASS, the aforementioned advantages still make them desirable for this application.

Rain and Weather Prediction

Currently the National Weather Service (NWS) has undertaken a massive program to update and modernize its data systems and forecast services. Resources are being earmarked to deploy 116 NEXRAD weather radars, launch additional GOES satellites, upgrade computer hardware, improve forecast models, and enhance surface weather monitoring. As the spatial resolution of weather forecasting models increase, there has been a growing interest in low-cost, autonomous sensors which improve spatial coverage. Low-cost radiometers could be an effective adjunct to the existing sensor complement.

Cloud sensing is an application where radiometers could clearly enhance existing and planned climate and weather observing networks. As stated earlier, radiometric sensing of clouds is the only technique capable of determining the **total** liquid content of clouds. Therefore, radiometers are able to monitor the total atmospheric water burden (liquid and vapor) in real time. It seems intuitive that a radiometric network that maps overhead water burden would improve weather forecasts.

Water vapor radiometers could enhance the NEXRAD radar product. As stated earlier, radar echoes are better correlated with size and shape of cloud droplets than with their liquid content. Concurrent WVR measurements can be used to relate liquid content of clouds to the radar returns. The NOAA Wave Propagation Laboratory has conducted preliminary studies showing value in radiometer support for radar measurements [12].

Finally, it should be noted that weather forecasting on the west coast of the United States suffers from the lack of data available over the ocean. Radiometer technology is also well suited for

deployment on ocean buoys. Several years ago, JPL developed a combined MTP/WVR data buoy for NOAA. Although NOAA continues to support radiometer development and demonstrations, NWS has not incorporated radiometers into their system **upgrade** partially due to their high cost.

Aircraft Icing Detection

Aircraft icing poses a serious winter hazard at many U.S. airports [3]. In freezing conditions, clouds can form with appreciable amounts of supercooled liquid water. Aircraft traversing these clouds accumulate ice as liquid freezes to the wings and fuselage. This adds weight and increases drag. This hazard is most acute during descent prior to landing due to the airframe's sub-freezing temperature. Fortunately, commercial jets are equipped with anti-icing systems such as wing heaters. However, light and ~~ilc~~(lcr;ite-size.(1 aircraft are usually unprepared to deal with severe winter icing. These aircraft would benefit from a ground-based airport surveillance system that can detect the presence of supercooled cloud liquid. Air traffic controllers who have been alerted to icing hazards can then appropriately advise and reroute vulnerable aircraft.

FAA-sponsored studies conducted by the NOAA Wave Propagation Laboratory demonstrate that passive microwave remote sensing techniques in conjunction with ceilometers or weather radars can identify winter icing hazards [3]. The ground-based microwave radiometers are sensitive to cloud liquid while being insensitive to ice. (Below 40 GHz, liquid water radiates more than two orders of magnitude more energy per unit mass than ice [13].) Once liquid is detected, its temperature must be assessed. Combining the temperature profile with a ceilometer or radar measurement of cloud height furnishes an estimate of cloud temperature. When cloud liquid is present in sub-freezing clouds an alert can be issued to air traffic control. The NOAA group participated in a multi-year icing detection demonstration project, Winter Icing and Storm Program (WISP) at Denver's Stapleton airport that clearly established the value of radiometric measurements for icing hazard forecasting [14].

Climate Monitoring and Global Change

Recent measurements of increases in the concentration of greenhouse gases such as carbon dioxide and methane has sparked concern that we are changing our climate. In the debate over anthropogenic climate change, the accuracy of climate predictions has come under scrutiny. There are significant model uncertainties associated with the effects of water vapor and clouds on climate. Water vapor, the earth's principal greenhouse gas, represents a significant source of modeling error. Clouds can cool the earth by reflecting solar radiation back towards space or can warm the earth by reducing surface heat (1 R) radiated to space. The total radiative effects of atmospheric water depend on its altitude, phase (vapor, liquid, or ice), and concentration.

Given the policy implications of global warming, several national and international programs are charged with improving the reliability of climate models. The Department of Energy's Atmospheric Radiation Measurement (ARM) program is an example of a program tasked with validating and improving the performance of global climate models [15]. ARM's charter is to improve the performance of general circulation and related atmospheric models as tools for predicting global and regional change. ARM recently began to instrument a cloud and radiation testbed (CART) in Oklahoma to provide data on the Earth's radiation balance spanning 90,000 km²,

roughly the size of a climate model cell. They have plans to eventually instrument five more sites in regions with diverse climatic characteristics. The Oklahoma CART site is instrumented with a variety of remote sensing instrumentation including RASS temperature profilers, a LIDAR, wind radars, a WVR, a whole sky imager, ceilometers, etc. To realize their goals, ARM researchers have identified critical measurement needs including measurement of horizontal distribution of total-column cloud liquid and water vapor as well as, cloud mapping/imaging capability. ARM is also interested in airborne and ground-based temperature profiles. Some of these needs can be met with radiometers, however their use has been limited by cost.

The Global Energy and Water Cycle Experiment (GEWEX) is an example of international effort to improve the understanding of the earth's energy fluxes and hydrological cycle. A significant objective of this program is to understand the impact of atmospheric water on weather and climate [16]. The Global-Scale International Project (GSIP) is the focus of the GEWEX buildup phase which is funded through NOAA, DOE, and NASA. [16], The goal of GSIP is to observe and model hydrological processes in the Mississippi River basin. This experiment will take advantage of a dense network of existing and planned atmospheric sensing systems. As in the case of ARM, the use of radiometers has again been limited by cost.

Finally, radiometric sensing could remedy inadequacies with surface cloud observations. Existing records of cloud cover are unreliable because of their subjective nature and dependence on weather observer training. Establishment of a 30 or 90 GHz standard data type for cloud liquid would go a long way toward generating a cloud record that could document climate change.

CONCLUSIONS

There is potential for widespread application of water vapor radiometers and microwave temperature profilers to monitor the atmosphere. Applications discussed in this paper include weather prediction, climate monitoring, pollution forecasting, and aircraft icing detection. This market can be stimulated by a reduction in the cost of radiometers. It is believed that significant price reductions can be achieved through mass production, application-specific designs, and use of MIC and MMIC technology.

ADDITIONAL INFORMATION

There is a vast technical literature on all aspects of radiometry including radiometer design, retrievals, and applications. Good starting points are two general references on radiometry: *Atmospheric remote sensing by microwave radiometry* [3] which is a collection of review articles written by the experts in the field, and *Microwave remote sensing, active and passive* [13] which is a three volume text discussing all aspects of microwave remote sensing. Also, having developed satellite, airborne, and ground-based radiometers for a variety of remote sensing applications, JPL can be used as a resource for further information on radiometry. Finally, both NASA and JPL have a strong commitment to technology transfer and would be potentially interested in teaming with companies interested in commercializing radiometers.

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